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**U.S. Patent Application For**

**A PHASED ARRAY COIL ASSEMBLY AND  
METHOD AND SYSTEM FOR EMPLOYING  
THE SAME**

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## A PHASED ARRAY COIL ASSEMBLY AND METHOD AND SYSTEM FOR EMPLOYING THE SAME

### 5 BACKGROUND OF THE INVENTION

The invention relates generally to a phased array coil assembly and more specifically to a phased array coil assembly for use in Magnetic Resonance Imaging (MRI).

10 Magnetic resonance imaging systems have found increasing applicability for a variety of imaging tasks, particularly in the medical field. Such systems also typically include coil assemblies for generating radio frequency (rf) magnetic fields used to control and excite spin systems in a subject of interest, such as in soft tissues of a patient. A body coil is typically employed for generating a highly uniform rf magnetic field transverse to the direction of the main, magnetic field direction. A series of gradient coils generate spatially varying magnetic fields to select a portion of the subject to be imaged, and to spatially encode sensed signals emitted by unitary volumes within the selected slice. The field gradients may be manipulated to orient the selected image slice, and to perform other useful imaging functions. Signals of a particular frequency acquired during application of the field gradient may be assumed to originate at a given position within the field gradient. The application of such a field gradient is also referred to as frequency encoding.

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20 Sensing coils are employed in conventional MRI systems and are adapted to the particular type of image to be acquired. Such sensing coils are highly sensitive to emissions from the subject positioned within the primary and gradient fields. Such emissions, collected during data acquisition phases of imaging, serve to generate raw data signals which may be processed to extract information relating to the nature and location of different tissue types in the subject. Where the region to be imaged is relatively small, a single channel surface coil may be employed. For example, a linearly polarized shoulder coil is typically employed for producing images of a human shoulder. For larger images, large single coils may be employed, or multiple

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coils may be used, such as in “phased array” arrangements. However, the use of large surface coils tends to result in lower signal-to-noise ratios in the acquired image data. Generally, surface coils have limited field of view (FOV) and lead to inhomogenous spatial uniformity. Phased array coils overcome this problem. Phased array coil assemblies are, therefore, commonly employed to produce images of larger areas, while providing an acceptable signal-to-noise ratio. Typically, phased array coil assemblies consist of multiple, non interacting coils, having similar SNR as a surface coil, but the combined FOV of a larger coil. In addition, the penetration of array coils compensates for limited penetration of individual coils.

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In a typical phased array arrangement, several adjacent coils are provided for receiving the signals emitted by the spin systems of interest during the signal acquisition phase of imaging. The output signals from each of several adjacent coils are independently amplified in the preamplifiers prior to processing of the signals for generation of the image data.

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Use of phased array coils also impacts the formation of magnetic resonance (MR) images (either two dimensional i.e 2D or three dimensional i.e 3D) which takes place in the complex Fourier domain, called k-space. In a typical MR system, as described above, gradients of varied strength are applied in a perpendicular direction to the frequency encoding gradient using gradient coils, prior to acquisition of the signal, to thereby twist the phase of the nuclear spins by varied amounts. The application of such additional gradients is referred to as phase encoding. Frequency-encoded data sensed by the detector coils after a phase encoding step is stored as a line of data in the k-space matrix. Multiple phase encoding steps are performed in order to fill the multiple lines of the k-space matrix. An image may be generated from this matrix by performing a two-dimensional or three dimensional Fourier transformation of the matrix to convert this frequency information to spatial information representing the distribution of nuclear spins or density of nuclei of the image material. One of the time limiting factor in the formation of MR images is the process of filing up k-space with data, which is done in successive manner, one line at a time.

To overcome these inherent limits, several techniques have been developed to effectively simultaneously acquire multiple lines of data for each application of a magnetic field gradient. These techniques, which may collectively be characterized as "parallel imaging techniques", use spatial information from the radio frequency (rf) detector coils to substitute for the encoding which would otherwise have to be obtained in a sequential fashion using field gradients alone. The use of multiple rf detector coils has been shown to decrease image acquisition time. Several coil geometries have been attempted for use with these parallel imaging techniques for enhancing image acquisition time. Typically these include linear arrays of coils and spatial information is acquired from minimally overlapping coils. Multiplexed array having a circular symmetry having three component coils have also been suggested. These arrangements have limitations in terms of using complex computations or implementation limitations when larger number of coils are desired.

It is therefore desirable to have coil geometries which significantly reduce the computation load and lead to easy implementation in MRI systems.

#### BRIEF DESCRIPTION OF THE INVENTION

Briefly, in accordance with one aspect of the invention, a magnetic resonance (MR) system comprises a phased array coil assembly and a signal processing circuit. The phased array coil assembly comprises a plurality of coils which coextensively cover a predetermined area. Each of the plurality of coils comprises a different number of loops over the predetermined area and divides the predetermined area into at least three contiguous regions arranged linearly along the predetermined area. The signal processing circuit is coupled to the phased array coil assembly and receives a plurality of magnetic resonance signals detected by the plurality of coils of the phased array assembly. The signal processing circuit is configured to localize the plurality of magnetic resonance signals originating in at least one of the contiguous regions. In an alternate aspect, a method of using a phased array coil assembly in presence of a gradient field system comprises receiving a plurality of magnetic resonance signals using a plurality of coils of the phased array coil assembly and processing the magnetic resonance signals detected by the phased array coil assembly. These

plurality of coils coextensively cover a predetermined area. Each of the plurality of coils comprises a different number of loops over the predetermined area and divides the predetermined area into at least three contiguous regions arranged linearly along the predetermined area.

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#### BRIEF DESCRIPTION OF THE DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

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FIG. 1 is a schematic block diagram of an exemplary magnetic resonance (MR) imaging system suitable for use with the present invention embodiments;

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FIG. 2 is a diagrammatic view of a phased array coil assembly for use in the embodiment of Fig. 1 or independently;

FIG. 3 is a diagrammatic view of one variation of the phased array coil assembly of Fig. 2;

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FIG. 4 is a diagrammatic view of another variation of the phased array coil assembly of Fig. 2;

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FIG. 5 is a diagrammatic view of one aspect of the signal processing circuit for use in the embodiment of Fig. 1; and

FIG. 6 is a diagrammatic view illustrating the connections in one exemplary embodiment of the signal processing circuit of Fig. 5.

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#### DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Referring now to Fig. 1, a magnetic resonance imaging system, designated generally by the reference numeral 10, is illustrated as including a magnet assembly

12, control and acquisition circuit 14, system controller circuit 16, and an operator  
interface station 18. The magnet assembly 12, in turn, includes coil assemblies for  
selectively generating controlled magnetic fields used to excite gyromagnetic  
materials spin systems in a subject of interest. In particular, the magnet assembly 12  
5 includes a primary coil 22, which will typically include a super conducting magnet  
coupled to a cryogenic refrigeration system (not shown). The primary coil 22  
generates a highly uniform magnetic field along a longitudinal axis of the magnet  
assembly. A transmit coil assembly 24 consisting of a series of gradient coils and a  
transmit RF coil is provided for generating controllable gradient magnetic fields  
10 having desired orientations with respect to the subject 30, and particularly with  
respect to the region of interest which is illustrated as predetermined area 50. In  
particular, as will be appreciated by those skilled in the art, the transmit coil assembly  
24 produces fields in response to pulsed signals for selecting an image slice, orienting  
the image slice, and encoding excited gyromagnetic material spin systems within the  
15 slice to produce the desired image. A receiving coil assembly, which is a phased array  
coil assembly 26, according to one aspect of the invention, is provided for detecting  
emissions from gyromagnetic material spin systems within the predetermined area 50,  
during data acquisition phases of operation of the system and is elaborated further in  
description below. A table 28 is positioned within the magnet assembly 12 to support  
20 a subject 30.

In the embodiment illustrated in Fig. 1, the control and acquisition circuit 14  
includes coil control circuit 32 and signal processing circuit 34. The coil control  
circuit 32 receives pulse sequence descriptions from the system controller 16, notably  
25 through the interface circuit 36 included in the system controller 16. As will be  
appreciated by those skilled in the art, such pulse sequence descriptions generally  
include digitized data defining pulses for exciting the coils the transmit coil assembly  
24 during excitation and data acquisition phases of imaging. Fields generated by the  
coils transmit coil assembly 24 excite the spin system within the subject 30 to cause  
30 emissions from the material, particularly the region of interest or a predetermined area  
50 within the subject 30. Such emissions from the predetermined area 50 are detected  
by a receiving coil assembly 26 and are filtered, amplified, and transmitted to signal

processing circuit 34. Signal processing circuit 34 may perform preliminary processing of the detected signals also described in detail below, and further perform amplification of the signals. Following such processing, the amplified signals are transmitted to the interface circuit 36 for further processing.

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In addition to the interface circuit 36, the system controller 16 includes central processing circuit 38, memory circuit 40, and interface circuit 42 for communicating with the operator interface station 18. In general, the central processing circuit 38, which will typically include a digital signal processor, a CPU or the like, as well as associated signal processing circuit, commands excitation and data acquisition pulse sequences for the magnet assembly 12 and the control and acquisition circuit 14 through the intermediary of the interface circuit 36. The central processing circuit 38 also processes image data received via the interface circuit 36, to perform 2D Fourier transforms to convert the acquired data from the time domain to the frequency domain, and to reconstruct the data into a meaningful image. The memory circuit 40 serves to save such data, as well as pulse sequence descriptions, configuration parameters, and so forth. The interface circuit 42 permits the system controller 16 to receive and transmit configuration parameters, image protocol and command instructions, and so forth.

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The operator interface station 18 includes one or more input devices 44, along with one or more display or output devices 46. In a typical application, the input device 44 will include a conventional operator keyboard, or other operator input devices for selecting image types, image slice orientations, configuration parameters, and so forth. The display/output device 46 will typically include a computer monitor for displaying the operator selections, as well as for viewing scanned and reconstructed images. Such devices may also include printers or other peripherals for reproducing hard copies of the reconstructed images.

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The technique described below may be equally well applied to various alternative configurations of magnetic resonance systems and scanners, including smaller scanners, and scanners incorporating single channel, phased array and similar

receiving coil structures. Moreover, the signal combining techniques described below may find application outside of the field of magnetic resonance imaging, and outside of the field of medical imaging in general.

5        A magnetic resonance imaging system 10 of Fig. 1, in one aspect comprises a phased array coil assembly 26 as illustrated on the right side in Fig. 2. The coil assembly 26 includes a plurality of coils 52, which coextensively cover a predetermined area 50, which is the area of interest with the subject 30 as described with reference to Fig. 1. The plurality of coils 52 are configured such that they detect  
10      magnetic resonance signals from a same spatial sensitivity volume enclosed with the predetermined area 50. Each of the plurality of coils 52 comprises a different number of loops 54 over the predetermined area 50. Further, the coils 52 divide the predetermined area 50 into at least three contiguous regions 56 arranged linearly along the predetermined area 50. Fig. 2 depicts the predetermined area being divided into  
15      four contiguous regions A, B, C, D since in this exemplary embodiment four coils are employed. At least one loop of a respective coil of the plurality of coils 52 is configured to overlap a loop of another respective coil of the plurality of coils 52 to reduce mutual inductance between the plurality of coils 52. In one example, the plurality of coils 52 in the phased array coil assembly 26 comprise at least four coils  
20      52 coextensively covering the predetermined area 50.

In another specific example, the plurality of coils 52, in the phased array coil assembly 26, comprise four coils covering the predetermined area 50 as shown on left side in Fig. 2. These coils include, a first coil 58 forming a single loop 60 extending over the predetermined area 50; a second coil 62 forming two loops 64 over the predetermined area 50; a third coil 66 forming three loops 68 over the predetermined area 50; and a fourth coil 70 forming four loops 72 over the predetermined area 50.  
25      As would be appreciated by one skilled in the art, the four coils 58, 62, 66 and 70 overlap, such that the second coil 62 is coextensive with the first coil 58, the third coil 66 is coextensive with the second coil 62 and the fourth coil 70 is coextensive with the third coil 66 and provide the configuration of the coil assembly 26 on the right side of Fig. 2 and described hereinabove. The predetermined area 50, in this example  
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is divided into four contiguous regions 56, represented by A, B, C, D in Fig. 2 and arranged linearly along the predetermined area 50.

In yet another example as shown in Fig. 3, the phased array coil assembly 26 comprises a first phased array coil assembly 74 and a second generally similar phased array coil assembly 76 disposed orthogonal to the first phased array coil assembly 74. This arrangement is useful for quadrature detection in MRI. These first and second coil assemblies can have several variations. In one example, the first and second phased array coil assemblies are generally planar. In another example, the first and second phased array coil assemblies are generally curvaceous. In one specific example as shown in Fig. 4, the phased array coil assembly 26, further comprises a plurality of self similar assemblies 78 disposed to enclose a volume. The coil assemblies in these examples comprise the coil configuration as described hereinabove with reference to Fig 2.

In the examples of phased array coil assembly described hereinabove, each of the plurality of coils 52 is symmetrical about a horizontal and vertical axis with respect to the axis along which the plurality of coils 52 is arranged.

Further in the examples of phased array coil assembly 26 mentioned hereinabove, each of the plurality of coils 52 has a unique spatial phase sensitivity though the volume of spatial sensitivity covered by each coil is substantially the same (volume covering the predetermined area 50). As would be appreciated by one skilled in the art, the plurality of magnetic resonance signals received from the coil assembly 26 will vary in phase with position of the plurality of coils 52. Referring to Fig. 1, if A, B, C and D are considered as the regions for MR signal sources, each of these regions has a unique combination of phase shifts associated with it with respect to the four coils 58, 62, 66 and 70. If we depict the anticlockwise rotation as + and clockwise as -, we can draw a correlation between the coil rotation (phase) and the region of signal source as follows:

Coil/Region	A	B	C	D
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Coil 58	+	+	+	+
Coil 62	+	+	-	-
Coil 66	+	-	-	+
Coil 70	+	-	+	-

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10 Thus, combining the magnetic resonance signals appropriately, the signals from each region can be selectively detected:

Region A = Coil 58 + Coil 62+ Coil 66 + Coil 70,

15 Region B= Coil 58 + Coil 62 - Coil 66 - Coil 70,

Region C= Coil 58 - Coil 62 - Coil 66 + Coil 70 and

Region D= Coil 50 - Coil 62 + Coil 66 - Coil 70.

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The combination described hereinabove can be accomplished by using analog hardware before the digitization of signals or can be computed numerically after digitization. These aspects are elaborated in detail hereinbelow. As would be appreciated by one skilled in the art, the phase array coil assembly 26, as described hereinabove may have other applications and uses in fields different from MR imaging.

30 The imaging system 10 also comprises a signal processing circuit 34 coupled to the phased array coil assembly 26 for receiving a plurality of magnetic resonance signals which are detected by the plurality of coils 52. The signal processing circuit 34 is configured to localize these plurality of magnetic resonance signals originating in at least one of the contiguous regions 56.

The signal processing circuit 34, in one aspect as shown in Fig. 5, comprises a plurality of splitters 80 to split a plurality of magnetic resonance signals received from the plurality of coils 52. Fig. 5 illustrates the signals received from four coils 58, 62, 66 and 70. Each of the plurality of magnetic resonance signals is split into a first pair of signals 82 with 180 degrees phase shift and each of the first pair of signals 82 is further split into a second pair of signals depicted generally by the reference numeral 84, with 180 degree phase shift. The signal processing circuit 34 further comprises a combiner circuit 86 (including combiners 88) to combine the second pair of signals 84 received from the plurality of splitters 80 into combined signal 90. The combiner circuit 86 is configured to yield a selective combination of the plurality of magnetic resonance signals which correlates to an individual contiguous region 56, represented by A, B, C and D in Fig. 5. Fig. 6 illustrates the respective connections between the splitters 80 and combiners 88 in an exemplary embodiment to yield a combined signal 90 which can be correlated to the individual contiguous regions A, B, C, and D. As would be appreciated by one skilled in the art, the analog circuit may also employ 90 degree phase shifters in place of 180 degree phase shifters to achieve the desired combination of MR signals. Other additional features may also be used, for example each individual coil may be connected to its own receiver and data acquisition system in place of combiners.

The signal processing circuit 34, in another aspect is configured to convert the plurality of magnetic resonance signals detected by the plurality of coils 52 to a digital form and to perform localization computation to yield a selective combination of the plurality of magnetic resonance signals which correlates to an individual contiguous region 56. In one example the localization computation uses a Hadamard Transform.

Another aspect of the invention is a method of detecting and transmitting magnetic resonance signals. The method includes receiving and transmitting a plurality of magnetic resonance signals using a plurality of coils 52 of a phased array coil assembly 26, described hereinabove in reference to Fig. 2, Fig. 3 and Fig. 4. The

method also comprises overlapping the loops 54 of the plurality of coils 52 for reducing mutual inductances between the plurality of coils 52.

5 An alternate aspect is a method of using a phased array coil assembly 26 in presence of a gradient field system. This method includes receiving a plurality of magnetic resonance signals using a plurality of coils 52 of the phased array coil assembly 26 described in reference with Fig. 2, Fig. 3 and Fig 4, and processing these signals detected by the phased array coil assembly 26. The method for processing the signals comprises localizing the plurality of signals originating in at least one of contiguous regions 56 of the predetermined area 50 being imaged. Localizing, as described herein refers to correlating each of a contiguous regions 56 with a corresponding predetermined combination of a plurality of signals received from each of respective plurality of coils 52, using phase shifts of the plurality of magnetic resonance signals received from each of respective plurality of coils 52.

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15 Processing the magnetic resonance signals, in one example comprises using analog circuitry for splitting a plurality of magnetic resonance signals received from the plurality of coils 52 into a first pair of signals 82 with 180 degrees phase shift. Each of the first pair of signals 82 is further split into a second pair of signals 84 with 180 degree phase shift. Processing the magnetic resonance signals further comprises combining the second pair of signals 84 to yield a selective combination of the plurality of magnetic resonance signals which correlates to an individual contiguous region 56.

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25 Processing the magnetic resonance signals, in another example comprises converting the plurality of magnetic resonance signals detected by the plurality of coils 52 to a digital form and performing localization computation to yield a selective combination of the plurality of magnetic resonance signals which correlates to an individual contiguous region 56. In one example, the localization computation uses  
30 Hadamard Transform.

Another aspect of the invention is an image created using the methods described hereinabove.

While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It is therefore to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.